FATIGUE LIFE AND DYNAMIC RESPONSE OF SMA ACTUATORS

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Final report

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Introduction

The major objective of this project was to study the fatigue life and dynamic response of Shape Memory Alloy (SMA) actuators. The effective use of SMAs in actuators undergoing thermomechanical cyclic loading requires a good understanding and estimation of their behavior and fatigue life. The investigation involved an array tests for both complete and partial transformation under different constant load levels. A microstructural evaluation of failure mechanisms was also performed. In order to understand the dynamic response of SMAs, the project was subdivided into two main thrusts: modeling and experimentation of SMA devices for vibration isolation in space applications and modeling and experimentation of SMAs in shock absorption devices.

In order to provide a comprehensive overview of the project, the report is organized as follows. First, the two main subtasks related to the dynamic loading of SMAs are presented. This is followed by a description of the work done on fatigue life of SMA actuators. The report concludes with the most recent activities that has been performed and includes some future plans and goals. A list of publications based on the work performed during this project is also included.

Passive Vibration Isolation

Objectives: Vibration isolation between launch vehicle and payload is a necessity if the payload is to survive it's journey into orbit. An investigation has been performed to determine the suitability of SMA for the task of vibration isolation. In this task, the effect of pseudoelastic response of shape memory alloys on passive vibration isolation and damping has been presented with payload launch applications in mind.

The methodology followed for this work was a) design and testing of a prototype SMA vibration isolation device. b) Development of a phenomenological and system ID-based models to predict the component level response of SMA springs and c) design and implementation of vibration isolation simulation tool. Figure 1 shows the SMA device vibration setup. Figure 2 shows a schematic of the device along with the testing system. The SMA tubes that were used as springs were created from tubing manufactured by

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14. ABSTRACT
The major objective of this project was to study the fatigue life and dynamic response of Shape Memory Alloy (SMA) actuators. The investigation involved an array tests for both complete and partial transformation under different constant load levels. A microstructural evaluation of failure mechanisms was also performed. In order to understand the dynamic response of SMAs, the project was subdivided into two main thrusts: modeling and experimentation of SMA devices for vibration isolation in space applications and modeling and experimentation of SMAs in shock absorption devices.

Major accomplishments of this project are summarized as follows:
- Development of two models for analysis of SMAs based dynamic systems
- Development of a computationally efficient simulation tool for parametric analysis.
  Capability includes
    - Isothermal, non isothermal conditions

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SMA, Inc. (6.0mm OD, ~5.65mm ID). Due to the small size of the tubes, they were operated in compression only. Testing of the prototype device was conducted at the Air Force Research Laboratory, Kirtland AFB, NM under the supervision of Dr. Kyle Henderson. Figure 3 shows comparison of model predictions along with experimental correlations with one of the tested cases.

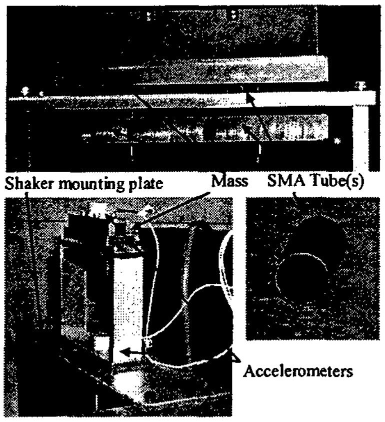

Figure 1 – SMA device vibration test setup

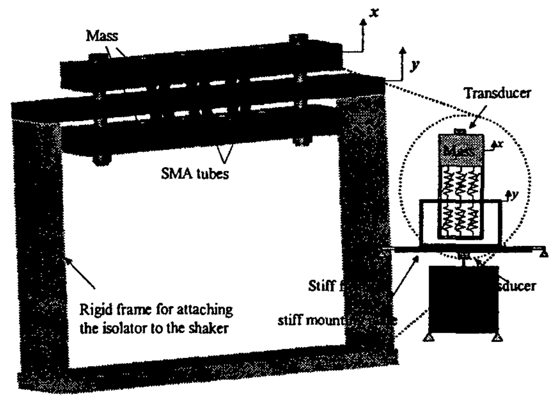

Figure 2 - Schematic of shaker and SMA spring-mass isolation system as tested

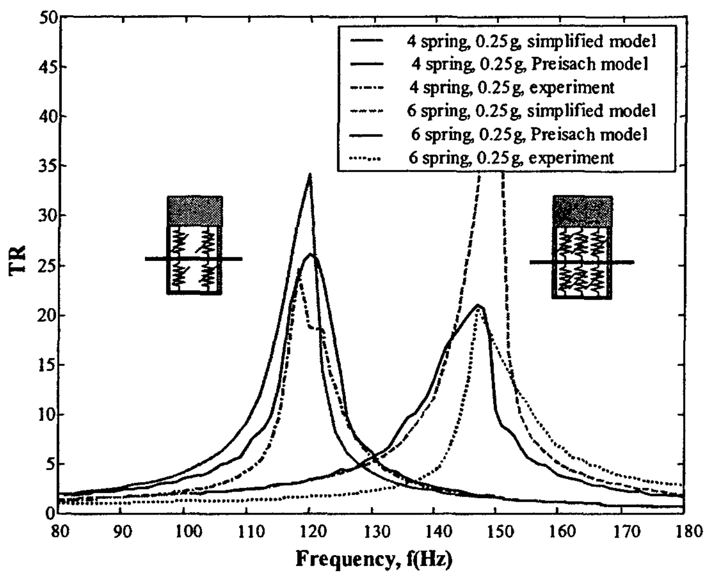

Figure 3 -Model and experiment show good agreement between measured and calculated resonant frequencies for varied spring pre-compression and number of springs for 1Kg mass.

Major accomplishements of this project are summarised as follows:

- Development of two models for analysis of SMAs based dynamic systems
- Development of a computationally efficient simulation tool for parametric analysis. Capability includes
  - Isothermal, non isothermal conditions
  - Linear, non-linear and non-linear with hysteresis
- Modeling of accurate SMA response using Preisach model for predicting the dynamic behavior of the SMA based vibration isolation device.

- SMAs are promising candidates for vibration isolation components based on:
    - Variable damping depending on loading
    - Tunable response (pre-compression)
    - Passive dual use structural member
- *Patent application in collaboration with AFRL for a Pseudo-Elastic Shape Memory Alloy Vibration Isolator.*

Dynamic Loading

Objectives: An investigation of the energy absorption capabilities of SMA components requires a detailed knowledge of the wave propagation phenomena in this type of nonlinear materials. A necessary first step in analyzing complex SMA devices is the study of one-dimensional rods. A numerical treatment is needed since closed form solution can only be obtained in certain very limited cases. The objective of the dynamic loading simulations was to build a reliable FE code and use it to analyze a wide variety of impact problems at different temperatures and boundary conditions.

An FE code has been developed to model wave propagation in one-dimensional SMA rods. A material subroutine implementing a constitutive model for polycrystalline SMA was also developed. It is capable of simulating both the phase transformations from martensite to austenite as well as detwinning of martensite. The fully coupled thermomechanical problem was solved by a standard semi-discrete FE formulation. Earlier attempts to solve the same problem with a commercial solver (ABAQUS) failed due to the complex material behavior of the SMA and the black-box nature of the solver. An adaptive mesh refinement strategy based on the Zienkiewicz-Zhu error estimator has been employed to considerably optimize the effectiveness of the FE analysis. A pulse-loading problem in detwinning was solved numerically and compared with existing experimental results.

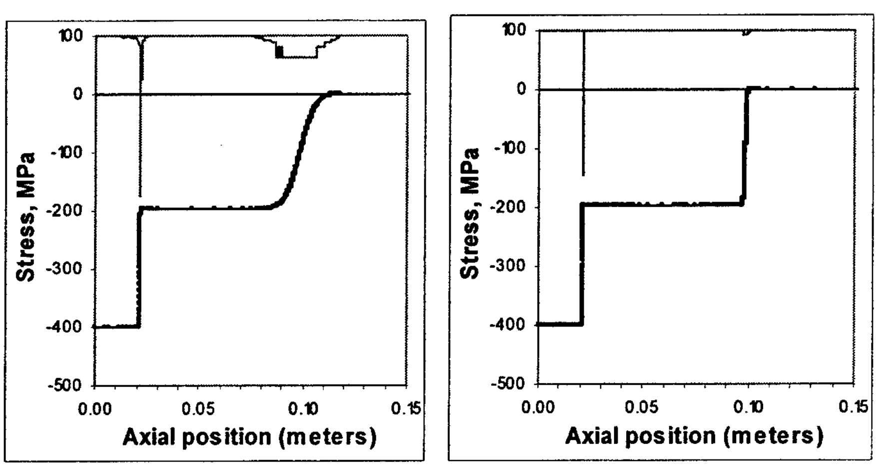

Figure 4 – Step loading problem. Shown is stress profile at 30μs for an adaptive mesh with two different time steps. The two-shock structure of the solution is clearly visible. Mesh nodes are marked with black squares and the thin line at the top shows the density of elements. The elastic shock is smeared in the left plot due to the coarse time step – 0.1μs. The time step for the right plot is 0.001μs and the solution is converging the analytical results.

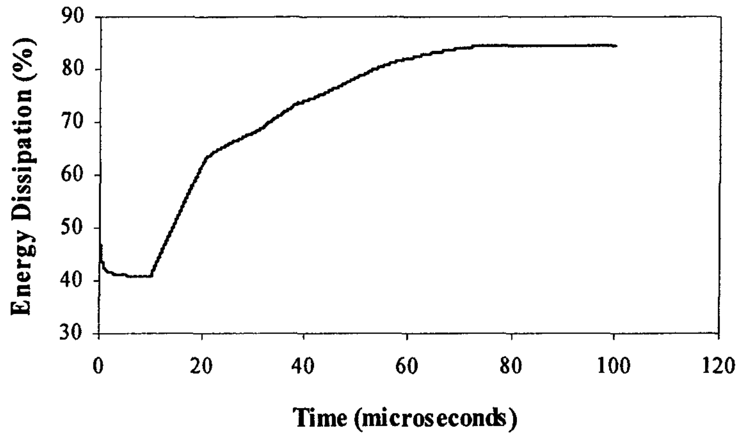

Figure 5 – Energy dissipation for a 10 μs square pulse in adiabatic conditions. Temperature is set for pseudoelastic response of the material.

The first boundary value problem that was solved was one for a step loading at isothermal conditions. The stress/strain profile for a constant shock load in SMA rods splits into an elastic precursor wave that travels at the speed of sound in the initial phase of the rod followed by a transformation front, as shown in Figure 4. Thermal effects were also included in the simulations and the adaptive meshing proved to work equally well. A model problem for a 10μs pulse under adiabatic conditions showed that up to 84% of the energy is dissipated (Figure 5) by transforming the mechanical energy of the shock wave heat. Dynamic response of SMA rods at lower temperatures involving the shape memory effect as the main factor for inelastic deformations was also considered. Energy dissipation levels reached similar values (86%) for a 10μs pulse. Finally, experimental data from a split-Hopkinson bar test was compared with numerical simulations and the two were found to be in good agreement (Figure 6).

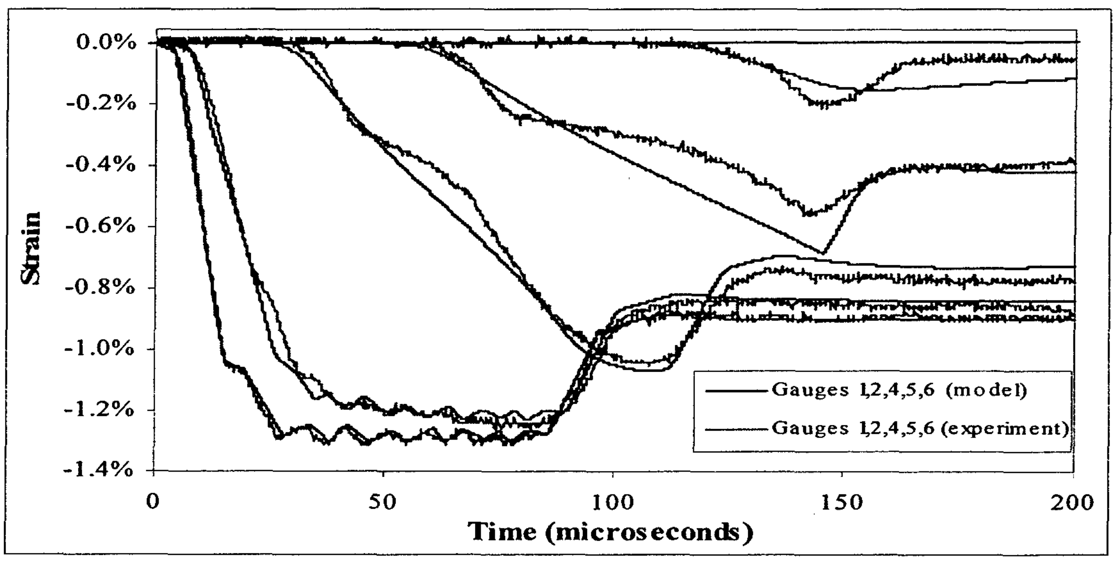

Figure 6. Data from a split-Hopkinson bar test of an SMA specimen instrumented with 6 strain gauges (red lines) is compared with model predictions (black). Gauge #3 was excluded as it failed during the test.

Major accomplishements of this part of the effort are summarised as follows:

- Development of specalized adaptive FEM solver that can sucessfully solve dynamic problems for materials with highly nonlinear constitutive response, such as SMAs.
- Good correlaion of numerical simulations with actual experimental results.
- Based on numerical simulations, SMA based devices
    - Show very good energy absorption capabilities.
    - Can absorb shock loads while preventing permanent damage to the material

Fatigue of SMA actuators

Objective: The effective use of SMAs in actuators undergoing thermomechanical cyclic loading requires a good understanding and estimation of their behavior and fatigue life. Arrays of tests were performed for both complete and partial transformation under different constant load levels (54 MPa to 247 MPa). The study included macroscale behavior characterization and also microstructural observations.

A large test matrix has been realized on an experimental fatigue frame to compare the fatigue life in specimens undergoing complete and partial transformations. The same testing and loading conditions were used for two cases: a complete transformation and a partial one with a volume fraction of martensite reaching up to 50%. After the experiments were completed the microstructure and patterns responsible for different failure modes were investigated.

The macroscale study of the fatigue life of SMA actuators was focused on the evolution of the different strains characterizing SMA actuation (martensitic, austenitic and transformation strains) as described for both complete and partial transformations under 192 MPa in Figures 7 and 8. Based on experimental results, a Manson-Coffin law (Figure 9) is used to express a relationship between plastic strain and number of cycles to failure. The graph indicates that minor loops lead to longer fatigue life due to lower amount of plastic strains accumulated during the cycling.

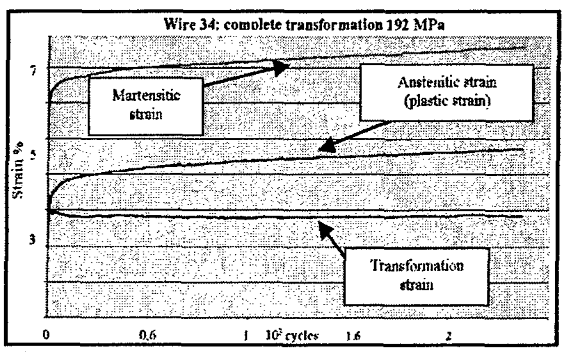

Figure 7. Complete transformation:
ε-N curve for a constant load of 192 MPa.
$N_f = 2500$.

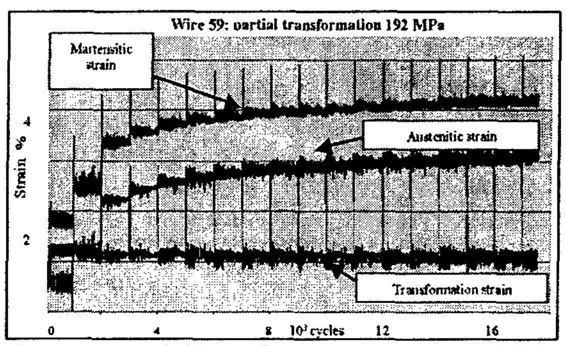

Figure 8. Partial transformation:
ε-N curve for a constant load of 192 MPa.
$N_f = 17000$.

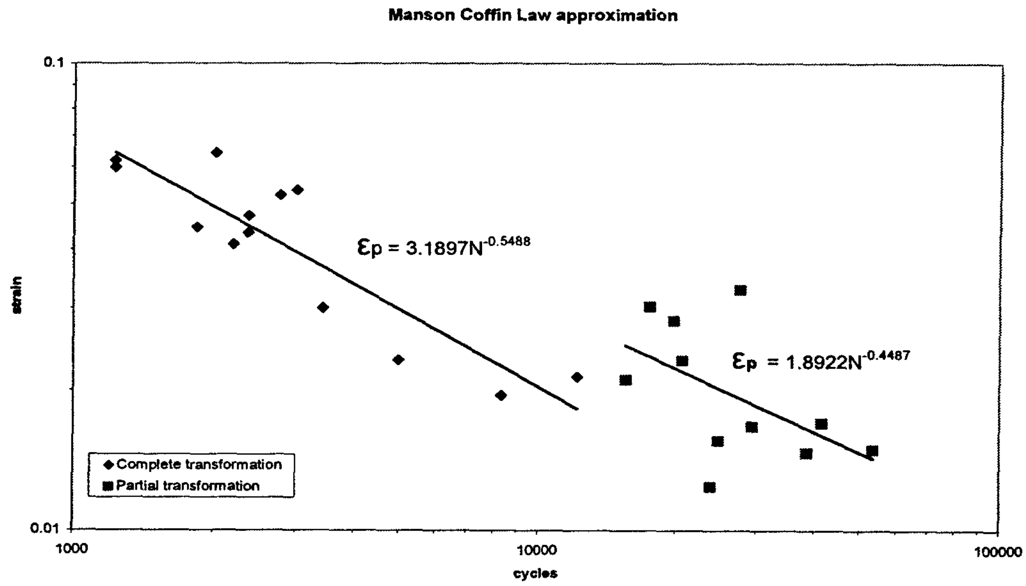

Figure 9. Manson-Coffin Law characterizing the plastic strain developed during complete and partial phase transformations.

The observation of the macroscale behavior was then followed by a microstructural investigation of the fracture modes using SEM. The fracture surfaces show two different levels of failure. One is called "classical", with the orientation and the propagation of the fatigue lines from the crack initiation area (Figure 10). However, another pattern was also identified: when exceeding 154 MPa for the complete transformation and 106 MPa for the partial transformation, a highly stressed state is observed in the specimens with circular cracks and internal cracks as seen in Figure 11. An interesting result is that the stress limit to start creating highly stressed state in the specimens is lower in the partial transformation: 154 MPa for the complete transformation in opposition to 106 MPa for the partial transformation.

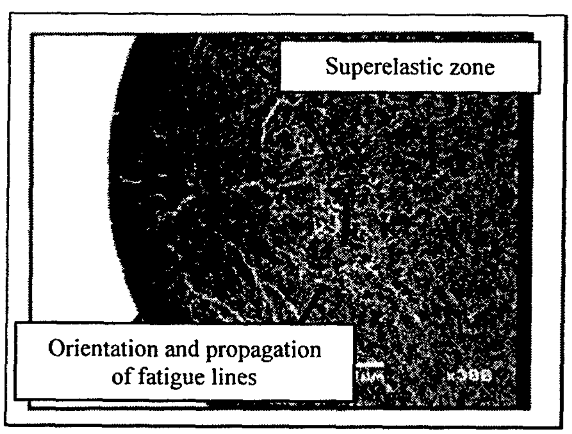

Figure 10. Complete transformation under 106MPa. Classic fracture surface describes the propagation and saturation at the main fatigue lines.

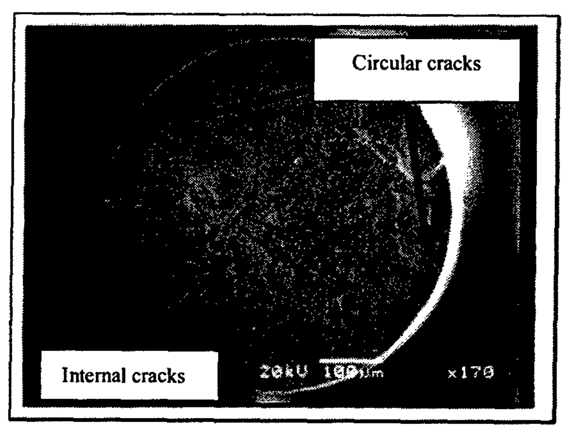

Figure 11. Complete transformation under 247 MPa. Higher internal stress level creates circular and internal cracks.

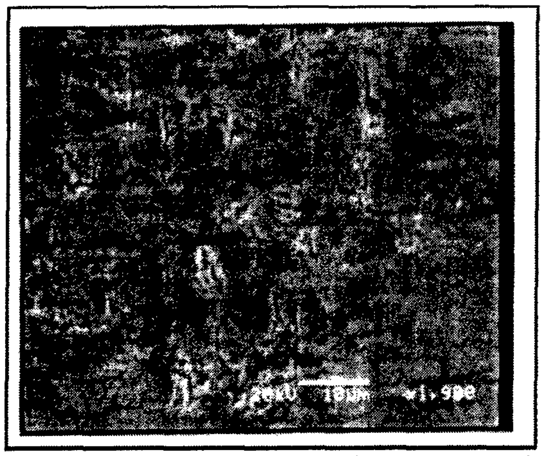

Figure 12. Complete transformation under 106MPa. Classic fracture surface describe the propagation and saturation at the main fatigue lines.

Figure 13. Complete transformation under 247 MPa. High internal stress levels create circular and internal cracks.

A general damaging pattern was also analyzed with microscattering of the superficial layer containing microcracks of 1 to 5 microns (Figure 12). Indications were found that the accumulation of stabilized detwinned martensite creates a debonding at the outer layer. It can be observed that the grain and microcracks sizes are almost identical suggesting that the impact of corrosion during cycles is significant. Further evidence that corrosion takes place during cycling, in particular at higher stress levels, is the fact that some macrocracks follow a random path through the debonded cells as shown in Figure 13.

Moreover, as the specimens are heated up through resistive heating and cooled down with a glycol-like liquid, some interactions with corrosion and oxidation effects are observed and could be responsible for the rising of some periodical circular cracks with the martensitic transformation. Indeed, while stretched into martensitic phase, the material is under tension and the superficial layer, a mixture of NiTiCu and oxidants, exhibits a brittle behavior favoring periodical circular cracks. The depth of these cracks is connected to the time spent in the coolant. As a simplified theory, the assumption of cyclic insertion of corroded particles could be an explanation for the growth of the hardened outer layer.

Major accomplishements of this part of the effort are summarised as follows:

- A Manson-Coffin type of law was used to successfully characterize the plastic strain increase (comparison between a complete and a partial martensitic phase transformation).
- Microstructural observations show a coupling of chemical interactions (due to active cooling) with mechanical damage, which further reduce the fatigue life of SMA actuators.

Current Activities and Future Work: Development of Comprehensive SMA Model.

The analysis of the existing SMA models during this project and their comparison to experimental results has shown that current constitutive models can handle successfully different types of thermomechanical loading paths but have difficulties doing so in a unified manner. While the models which take into account the development of stress-induced martensite have

reached a high level of sophistication, generally they lack the ability to handle other loading paths, involving detwinning and reorientation of martensite. The simulations involving dynamic loading of SMAs ran into this type of difficulties and it was necessary to use different models for different temperature regimes. Another limiting factor in existing SMA models are related to their inability to model successive tension-compression cycles. Therefore most of the current research is focused towards developing a comprehensive SMA model that can remedy these issues. The goals of this effort are summarized bellow:

- Utilize two internal variables for phase transformation in order to treat pseudoelasticity and detwinning in a unified manner in three dimensions;
- Use a different hardening law for the detwinning deformation which takes into account the gradual decrease in stiffness;
- Introduce new laws for the evolution of internal variables, so that successive tension–compression cycles can be accurately modeled.

The starting point was to extend the current SMA model that was developed in our group to one with two internal variables. This allowed to successfully model the different hardening behavior of pseudoelasticity and detwinning within a unified framework (Figure 14). The next task was to simulate loading paths that involve simultaneous transformations of austenite to both twinned and detwinned martensite. A loading path involving constrained cooling of an SMA specimen, initially loaded in austenite demonstrates these capabilities (Figure 15).

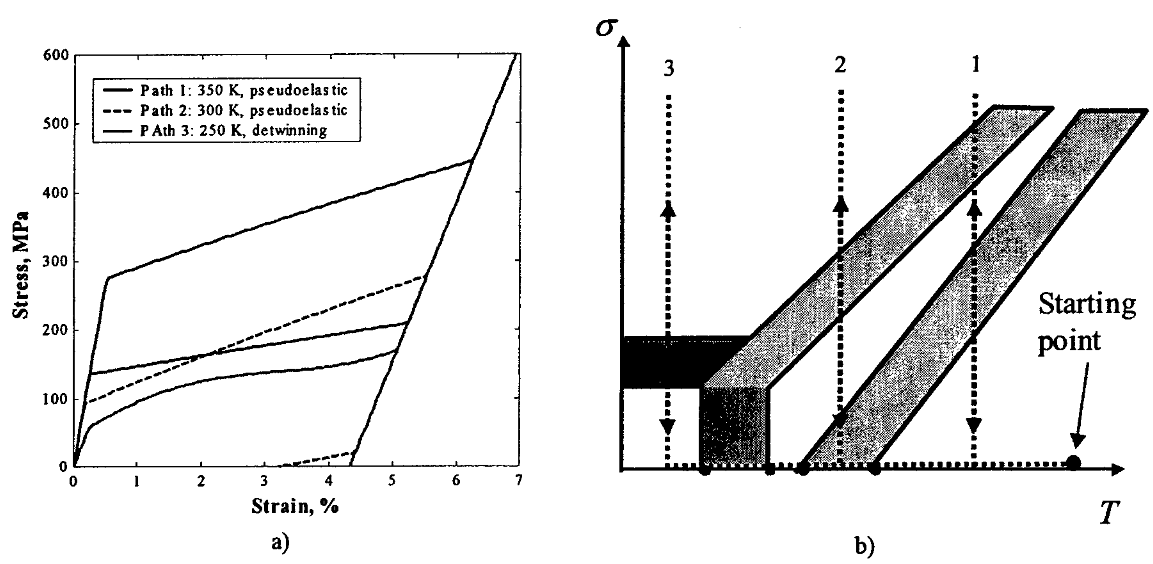

Figure 14. The new comprehensive model uses a different hardening law for phase transformation and detwinning of martensite as can be seen from the stress-strain plots a). A schematic of the simulated loading path is also shown on the stress-temperature phase diagram for the SMA b)

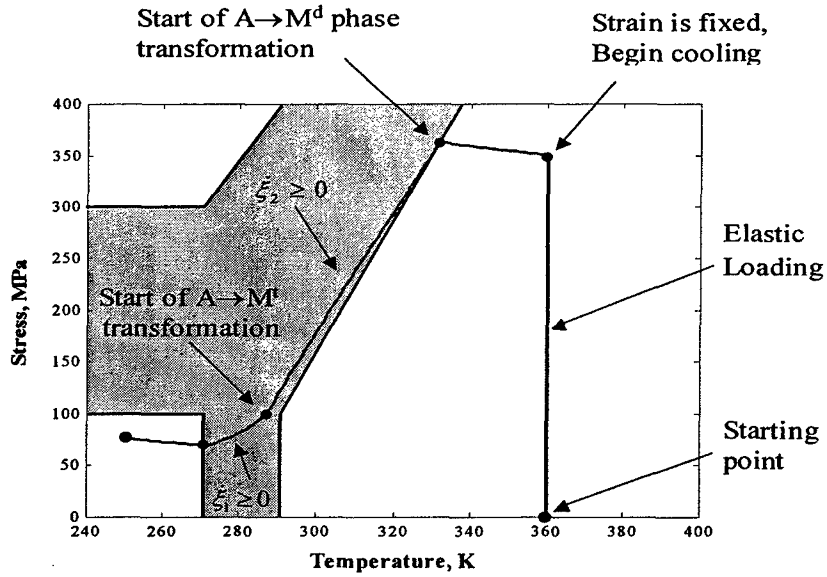

Figure 15. In a temperature-strain driven simulation an SMA bar is first loaded elastically in the austenitic phase. The strain is then fixed and the bar is gradually cooled. The blue line shows the resulting thermomechanical path in temperature-stress space.

While there is significant progress in the development of a comprehensive SMA model, this is a still ongoing area of research. It is necessary to validate the model on a comprehensive set of thermomechanical loading paths as well as to allow for the modeling of successive tension-compression cycles.

Publications

Journal Publications:

1. Lagoudas, D. C., Ravi-Chandar, K., Sarh, K. and Popov, P., "Dynamic Loading of Polycrystalline Shape Memory Alloy Rods", Mechanics of Materials, 35 (7): 689-716, 2003.

2. Bekker, A., Victory, J. C., Popov, P. and Lagoudas, D. C., "Impact induced propagation of phase transformation in a shape memory alloy rod", International Journal of Plasticity 18 (11): 1425-1647, 2002.

3. Strelec, J. K., Lagoudas, D. C., Khan, M. A. and Yen, J., "Design and Implementation of a Shape Memory Alloy Actuated Reconfigurable Wing", J. Intell. Mater. Systems Struct., 14 (4-5): 257-273, 2003.

4. Khan, M.M., Lagoudas, D.C., Mayes J.J., Henderson, B.K., "Pseudoelastic SMA Spring Elements for Passive Vibration Isolation, Part I: Modeling," Journal of Intelligent Material Systems and Structures, Vol. 15, No. 6, pp. 415-441, 2004.

5. Lagoudas, D.C., Khan, M.M., Mayes, J.J., Henderson, B.K., "Pseudoelastic SMA Spring Elements for Passive Vibration Isolation, Part II: Simulations and Experimental Correlations," Journal of Intelligent Material Systems and Structures, Vol. 15, No. 6, pp. 443-470, 2004.

6. Patoor, E., Lagoudas, D.C., Entchev, P.B. and Brinson, L.C. 2005, "Shape Memory Alloys – Part I: General Properties and Modeling of Single Crystals," Mechanics of Materials (accepted)

7. Lagoudas, D.C., Entchev, P.B., Popov, P. Patoor, E., Brinson, L.C. and Gao, X. 2005, "Shape Memory Alloys – Part II: Modeling of Polycrystals, Mechanics of Materials (accepted)

Conference Proceedings:

1. Lagoudas, D. and Popov, P., "Recent Advances on the Thermomechanical Modeling of Shape Memory Alloys, SPIE Conference, San Diego, CA, March 6-10, 2005
2. Popov, P. and Lagoudas, D., "Upscaling of Fluid Flow in Porous Shape Memory Alloys," SES Conference, Lincoln, NE, Oct. 10-12, 2004 (paper won 3rd place in Graduate Student Competition).
3. Lagoudas, D., Popov, P., and Iliev, O., "Constitutive Modelling of Shape Memory Alloys and Effective Properties of Fluid Saturated Porous Shape Memory Alloys, SES Conference, Lincoln, NE, Oct. 10-12, 2004
4. Lagoudas, D.C., Bertacchini O.W., Patoor E., "Fatigue Life Characterization of SMA Actuators undergoing thermomechanical cyclic loading", Proceedings of SPIE 2003 Smart Structures and Materials, Behavior and Mechanics, San Diego, CA, March 17-20, 2003.
5. Lagoudas, D. C., Popov, P., "Numerical studies of wave propagation in polycrystalline shape memory alloy rods," 10th Annual International Symposium on Smart Structures and Materials, SPIE Vol. 5053, pp. 294-304, San Diego, CA, March 2-6, 2003.
6. Lagoudas, D.C., Khan, M. M., Mayes, J. J. and Henderson. K.B., "Parametric study and experimental correlation of an SMA based damping and passive vibration isolation device", submitted to proceedings of IMECE'02, 2002 International Mechanical Engineering Congress and Exposition, New Orleans, LA, November 17-12, 2002.
6. Khan M. M. and Lagoudas D.C., "Modeling of Shape Memory Alloy springs using Preisach model for damping and passive vibration isolation", Proceedings of SPIE 2002 Smart Structures and Materials, San Diego, CA March 17 – 21, 2002.
7. Strelec, J. K. and Lagoudas, D. C., "Fabrication and Testing of a Shape Memory Alloy Actuated Reconfigurable Wing", Proceedings of SPIE 2002 Smart Structures and Materials, San Diego, CA, March 17 – 21, 2002.
8. Lagoudas, D.C., Khan, M. M. and Mayes, J. J., "Modeling of Shape Memory Alloy springs for passive vibration isolation", Proceedings of IMECE'01, 2001 International Mechanical Engineering Congress and Exposition, New York, NY, November 11-16, 2001.
9. Mayes, J. J. and Lagoudas, D. C., "An experimental investigation of shape memory alloy springs for passive vibration isolation", In Proc. Conf. AIAA Space 2001 Conference.
10. Lagoudas, D. C., Mayes, J. J. and Khan, M. M., "Simplified Shape Memory Alloy (SMA) Material Model for Vibration Isolation", 2001SPIE Conference on Modeling, Signal Processing and Control in Smart Structures, Newport Beach, CA, March 5-8, 2001.

PhD & MS Theses

1. Popov, Peter, "Constitutive Modelling of Shape Memory Alloys and Upscaling of Deformable Porous Media," PhD Dissertation 2005.
2. Entchev, Pavlin B., "Micromechanical Modeling of Porous Shape Memory Alloys," PhD Dissertation 2002.

3. Strelec, Justin, "Design and Implementation of a Shape Memory Alloy Actuated Reconfigurable Wing," MS Thesis 2002.
4. Khan, Mughees, "Modeling of Shape Memory Alloy (SMA) Spring Elements for Passive Vibration Isolation Using Simplified SMA Model and Preisach Model," MS Thesis 2002.
5. Mayes, John J., "Suitability of Shape Memory Alloys for Vibration Isolation with Application to Launch Vehicle Payloads," MS Thesis 2001.

Honors/Awards

Honor/Award: 2004 ASME Best Paper Award		Year received: 2005

Honor/Award Recipients:
Dimitris Lagoudas, Texas A&M University
John J. Mayes, Bell Helicopter
B. Kyle Henderson, AFRL
Mughees Khan, Texas A&M University

Awarding Organization: The American Society of Mechanical Engineers

Undergraduate Student Research
Allison Barnard
Kristen Golden
Eric Chastain
Chris Day
Melissa Laborde

Patents
"Passive Vibration Isolation Devices with SMAs," Joint AFRL and TEES, Patent Pending (2003)